

VLA Measurements of a sample of Planetary Nebulae

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Abstract. We report on new radio measurements of Galactic planetary nebulae, aimed at resolving the controversies on the reliability of older VLA flux densities and the suggested deviations from the standard Galactic extinction law found for planetary nebulae. We show that for faint (<10 mJy) objects observed at high angular resolution, previous determinations are indeed too low. For the bright objects we find no significant differences. The new values are the most accurate flux determinations yet for planetary nebulae, reaching 1% for the brightest objects in the sample. Based on the new data, we confirm that there is a systematic difference between the extinction derived from the radio/H β flux ratio and derived from the Balmer decrement, which led to the suggestion of deviations from the standard extinction law. However, final confirmation of this has to await the availability of more, accurate measurements of the Balmer (and/or Paschen) lines.

1. Introduction

In two recent papers (Stasińska et al. 1992; Tyllenda et al. 1992) it has been suggested that the ratio of total to selective extinction, R , is significantly lower than 3, the value corresponding to the standard extinction law. The authors find that for a sample of planetary nebulae (PN), the standard extinction law gives a higher extinction at H β from the observed Balmer decrement (effectively the H α /H β ratio) than is found from the measured radio to H β flux ratio. In other words, the observed radio flux is generally lower than predicted from the H β measurements and the Balmer decrement.

The analysis is based on various radio and optical measurements available in the literature. Most of the radio data comes from two papers, publishing data obtained with the Very Large Array: Aaquist and Kwok 1990, and Zijlstra, Pottasch and Bignell 1989. In the course of their

analysis Tyllenda et al. “suggest that the radio measurements of Pottasch’s group probably underestimate the radio fluxes ... The underestimate becomes more important for fainter objects, which seems to indicate a sort of instrumental cutoff.” We note that the faint objects (<10 mJy) all come from the sample of Zijlstra et al.: Aaquist and Kwok observed brighter sources only. Two reasons are suggested for the possible underestimation of the radio flux:

1. PN may be optically thick at 6 cm, the wavelength most often observed.
2. VLA measurements are insensitive to extended structures (larger than 10 times the beam size) which could lead to errors if either a too small beam was used or an extensive halo exists.

This suggestion can be checked by taking new measurements. In order to check the first point concerning the optical depth, measurements can be made at several wavelengths. For practical reasons both 3.6 cm and 6 cm can be measured, the wavelengths at which the system temperature is lowest. If the nebula is optically thin the flux density at 3.6 cm will be 5% lower than at 6 cm. If it is completely optically thick the flux density at 3.6 cm will be considerably higher than at 6 cm, the precise value depending on the geometry and the density distribution. In order to check the second point (extended structures), it is possible to increase the beam size by placing the telescopes closer together (C and D array in the VLA) than was the case in the earlier measurements. Information on the size of the object then becomes more uncertain or is completely lost, but the total flux now includes all possible extended structures. In addition to checking the earlier radio flux densities, such observations also allow us to study the first suggestion of the deviating selective extinction for planetary nebulae.

Because of practical considerations it was impossible to re-do all PN of interest. Enough time was allotted to re-do 20 PN. A sample was chosen between $l = 0^\circ$ and $l = 60^\circ$ for which the discrepancy between the extinction from the Balmer decrement and radio /H β ratio was large. The results of these new measurements are reported here.

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2. Measurements

The sources were observed at the VLA in September/October 1993, with the array in the C/D hybrid configuration. The hybrid configurations give the best beam shape for southern objects, and the C/D hybrid was chosen to obtain the largest point-spread function. The phase stability is also better at the compact (C,D) configuration, leading to better calibrated maps. The observations were therefore optimised for accurate flux determinations.

All sources were observed for 10 minutes at 6 cm and 4 minutes at 3.6 cm: the integration times can be shorter at 3.6 cm because the receivers are more sensitive. Flux calibration was done using 3C 286, which has a flux density of 7.55 Jy at 6 cm and 5.26 Jy at 3.6 cm (these values are recent determinations which are 1–1.5% higher than previous values). In fact the spectral index of 3C 286 is such that the flux density differs slightly for both IFs which constitute one wavelength band, at a separation of 50 MHz. The calibration took this into account. Calibration and imaging were done using the software package AIPS. Self calibration was applied in most cases, but was found not to increase the flux densities significantly for most sources. The rms noise in the final maps was 0.1 mJy or slightly lower at both wavelengths.

A problem was encountered with the AIPS calibration routine in those cases where the calibrator was only observed once, where the phase calibration was sometimes faulty. Luckily all affected sources could be self-calibrated. Flux densities were determined by integrating over the area of the source. Using the peak flux was not possible because even at the D-array these PN are slightly resolved. This introduces an uncertainty especially near the galactic centre, where the many confusing sources in combination with the poor UV coverage of short observations cause the field to show residual striping which cannot be removed. The uncertainty caused by this can be 1 mJy or more, although having two wavelengths helps: in general the confusion is less at 3.6 cm. Also, some sources appear to show evidence of extended emission, where the flux keeps rising if determined over larger areas. In such cases there is a larger uncertainty in the total flux density, since the sensitivity of the maps is insufficient to determine the full extent of the emission, and it is unclear whether the extent is indicative of an ionised halo or due to image residuals.

3. Comparison with previous observations

Table 1 gives the newly determined flux densities. The first column follows the naming convention adopted in the new Catalogue of Planetary Nebulae (Acker et al. 1992), which we recommend; the second column gives the name in the old system. Columns 4–6 list the previous 6 cm flux density and the new determinations at 6 and 3.6 cm. We note that the 3.6 cm flux is expected to be 5% below the 6

cm value if the radio emission is optically thin. This is, in fact, the case for most of our objects with the exception of PN 006.4+02.0, 007.5+07.4, 015.9+03.3, 032.1+07.0 and 043.1+03.8 which may show marginal optical depth effects. The flux densities are expected to be accurate to 1%, plus an added uncertainty due to image noise, which will be approximately 1 mJy or less. The fact that the expected spectral index is found even though the measurements at the two frequencies are independent of each other, indicates that the accuracy of the flux densities is good. These are the most accurate flux densities for PN yet determined, especially for the brighter objects where the signal to noise is highest.

However, the comparison of the previous measurement at 6 cm (Zijlstra et al., 1989; column 5 in Table 1) with the present measurements (column 6) gives reason for concern. Good agreement (within 10%) is obtained in only 50% of the cases (one of those, PN 032.1+07.0, was originally observed by Aaquist and Kwok, 1990, rather than Zijlstra et al.). Marginal agreement (15% to 50%) is obtained in 35% of the cases, and in 3 cases the differences are even larger. In 2 of these 3 cases, PN 000.2–01.9 and 024.8–02.7, the quality of the original image was very poor, as evidenced by a significantly higher noise than theoretically expected. In the case of PN 005.8–06.1 apparently a mistake was made in the calibration of the previous measurements. We finally note that for PN 015.6–03.0, the older map was based on a combination of several observations and is probably better than the present map due to better UV coverage.

There are 6 sources remaining in the sample with unexplained, large differences between the new and the old flux densities. All objects in our sample with significant discrepancies have three things in common: they were originally observed in the B-array (i.e. at high resolution), are relatively extended ($> 5''$, a few times the size of the beam) and are faint (of order 10 mJy or less). This suggests that over-resolution of faint sources is the cause of the problem. For comparison, we note that about 120 of the 300 objects in the Zijlstra et al. catalogue were observed in the B-array (the others were observed at lower resolution), and that of those 120 about 30 objects were fainter than 10 mJy and larger than $5''$.

Based on this, we suggest that the underestimation of the radio flux density was caused by a combination of two effects: First, it is very difficult to obtain an accurate flux density from a faint, extended source. At the time the previous observations were made, accurate diameters were often not available and errors were made in choosing the appropriate VLA configuration. Second, the phase calibration is more uncertain in the B-array, where significant phase changes can occur over a few minutes. During long integrations these errors tend to average out, but for short observations they cause significant scattering of flux into the side lobes of the beam. In general one use self-calibration to correct for phase errors, but this

Table 1. COMPARISON

	Name	ra,dec (1950)	S(6 cm) [mJy]		S(3.6 cm) [mJy]	Diameter*
			old	new	new	(arc sec)
000.2–01.9	pk0–1.5	17 50 33.7 –29 43 12	14.0	22.6	20.9	5
000.4–02.9	pk0–2.6	17 55 07.0 –30 00 24	5.5	7.4	7.0	7
000.7–03.7	pk0–3.1	17 59 06.6 –30 14 28	5.0	8.7	7.8	6
002.2–02.5	KFL2	17 57 50.1 –28 16 20	2.2	2.2	2.1	5.4
002.7–04.8	pk2–4.2	18 07 54.3 –28 59 42	24.0	28.5	26.7	9
003.9–02.3	pk3–2.1	18 00 31.9 –26 43 42	54.0	60.5	56.6	4.4
005.7–03.6	KFL13	18 09 38.7 –25 45 09	3.5	4.4	4.1	14.3
005.8–06.1	pk5–6.1	18 19 46.7 –26 50 52	3.5	20.5	18.7	5
006.4+02.0	pk6+2.5	17 49 40.1 –22 21 16	59.0	60.5	59.6	7
007.5+07.4	pk7+7.1	17 32 14.2 –18 32 26	3.5	7.8	8.4	6
009.8–04.6	pk9–4.1	18 22 03.6 –22 36 35	11.0	11.9	11.5	6
010.7–06.7	pk10–6.2	18 31 50.4 –22 45 42	3.0	5	4.2	7
015.9+03.3	pk15+3.1	18 04 40.9 –13 29 44	98.0	99.9	97.7	4
015.6–03.0	pk15–3.1	18 27 17.3 –16 47 23	10.0	–	13.2	52
022.1–02.4	pk22–2.1	18 37 34.1 –10 42 37	70.0	66.6	63.5	8
024.8–02.7	pk24–2.1	18 43 51.0 –08 31 18	3.0	12.0	11.4	5
032.1+07.0	pk32+7.2	18 22 13.6 +02 27 45	26.0	30.6	29.3	2.7
043.1+03.8	pk43+3.1	18 54 12.3 +10 48 10	22.0	23.0	22.8	4
052.5–02.9	pk52–2.2	19 36 53.3 +15 49 52	44.0	45.1	42.7	4.7
055.2+02.8	pk55+2.1	19 21 15.1 +21 02 08	32.0	34.9	32.2	2.3

* From Zijlstra et al. (1989), Aaquist and Kwok (1990) and Kinman et al. (1988).

requires sufficient signal to noise and is for short observations not possible below 10 mJy, especially for extended objects. Both of the discussed effects affect the same group of sources.

We conclude that of the two explanations for the low radio flux densities mentioned in the Introduction, the optical depth effects are not important, but extended structures are. However, the problem is not the insensitivity of the VLA to highly extended structures (which begins at larger angular diameters than found the objects observed here), but rather the decrease in signal to noise for objects a few times larger than the beam.

Since only about 7% of the original sample of Zijlstra et al. (1989) were re-measured, the question arises whether the remainder of the sample also contains PN whose flux densities have been underestimated. While nothing can be said with certainty, it seems likely that the worst cases were part of the sample which were re-measured. The reason for this is that this sample was chosen from among those cases where there was poor agreement with the optical measurements. We therefore expect that the accuracy of the remainder of the original sample is better. As mentioned above, about 30 objects (including the presently observed objects) fall in the 'danger zone', with diameter larger than 5'', flux density less than 10 mJy and originally observed in the B-array. All these should be re-observed. The catalogue of Aaquist and Kwok (1990) contains brighter sources and they also used longer integra-

tion times: we therefore expect that their catalogue will be less affected by these problems.

We finally note that the encountered problems appear to be inherent to snapshot observations, and that in the extended VLA configurations, longer observations are desirable to obtain accurate flux densities for extended objects.

4. Comparison of extinction

It may now be asked whether the new radio observations alter in any way the conclusions of Stasińska et al. (1992) and Tyllenda et al. (1992), discussed in the Introduction.

In Fig. 1 the value of $C (= \log[H\beta_{\text{exp}}/H\beta_{\text{obs}}])$, where $H\beta_{\text{obs}}$ is the observed $H\beta$ flux and $H\beta_{\text{exp}}$ is the value predicted from the observed radio data, is plotted as ordinate. The conversion from radio data to $H\beta_{\text{exp}}$ is made assuming the electron temperature (T_e) of the gas is 10^4 K and the He/H ratio is 0.1 with all the helium singly ionized. These assumptions could introduce a 20% error in $H\beta_{\text{exp}}$, but it is unlikely to be more than this. On the abscissa, the value of C is plotted, derived by assuming a standard extinction law (e.g. Seaton, 1979) and adjusting the amount of extinction so that the observed $H\alpha/H\beta$ ratio is reduced to the theoretically expected value at $T_e = 10^4$ K of 2.85 (Brocklehurst, 1971).

The open circles on Fig. 1 are measurements from the survey of Acker and Stenholm (Acker et al. 1991; Tyllenda et al. 1992). All nebulae which we have measured have

data from this source. The quality of these data varies, depending on the size and brightness of the nebula. For example, the $H\beta$ flux was measured with a square diaphragm $4''$ on a side. For larger nebulae a correction factor was applied, but this can be uncertain. The triangles in the figure use the same Balmer decrement but $H\beta$ fluxes which are more accurate, taken from Shaw and Kaler (1989), Webster (1983) and O'Dell (1963). A line connecting the circle and the triangle indicates that the same nebula is involved. Unfortunately only 6 PN have more accurate $H\beta$ flux measurements, but they indicate that the flux measurements of Acker et al. (1991) are accurate to the limits given by these authors¹.

The crosses in Fig. 1 indicate the few other measurements of Balmer decrements available in the literature (Shaw and Kaler 1989, Kinman et al. 1988, Aller and Keyes 1987, de Freitas Pacheco et al. 1992, Ratag 1991). As can be seen from the figure, in half the cases good agreement is obtained with the measurements of Tyllenda et al. while in the other half substantial differences are found. It is clear that more, careful measurements are desirable.

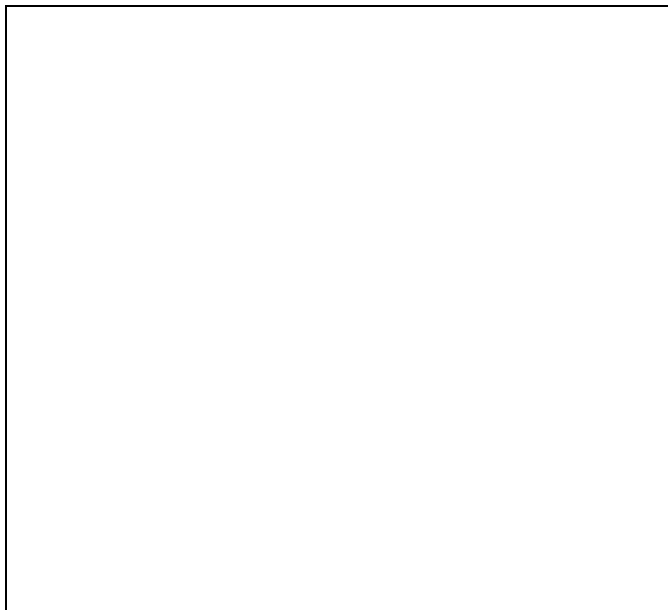


Fig. 1. The extinction coefficient c derived from the Balmer decrement versus the value derived from the radio/ $H\beta$ flux ratio, for the PN discussed in this paper. Open circles indicate measurements from Acker et al. (1991) and Tyllenda et al. (1992). The triangles present $H\beta$ fluxes from different papers, while the crosses present different measurements of the Balmer decrements (for references see text). The connecting lines indicate that the same nebula is involved.

¹ Kinman et al. (1988) also have measured $H\beta$ fluxes in about half of these objects. They are sometimes quite different from the measurements of Acker et al. and we have chosen to ignore them

As can be seen in Fig. 1, a straight line which best represents the observed circles is less steep than the 45° line shown in the diagram. This is also the conclusion of Stasińska et al. and Tyllenda et al. It indicates that the new radio measurements do little to affect this conclusion. This fact can be interpreted in two ways; either (1) the total to selective extinction is lower than 3.1, the standard extinction law, or (2) the observational errors, especially of the Balmer decrement, are still too uncertain to conclude that the points do not fit the 45° line. On the basis of the nebulae plotted in Fig. 1, the latter alternative appears quite real.

We note that a similar discrepancy, with radio flux density too low compared to the $H\beta$ flux, has recently been found for two HH objects: HH 32A and HH 1-2 (Anglada et al. 1992). Anglada et al. suggest as explanation the presence of significant shock excitation of the $H\alpha$ line, although they also note that the shock velocities in these objects appear too high for this mechanism to work. Since their observations were done in the VLA D-configuration, extended emission is not expected to contribute to the deficit. This provides still another possible interpretation of the discrepant measurements.

Whichever of these alternatives is correct however, one thing is certain: use of the value of C obtained from the Balmer decrement measures of Tyllenda et al. (1992) together with the standard extinction curve, will overestimate the extinction in the visual or ultraviolet. Thus this method should not be used, e.g. to correct the visual magnitudes of the central stars. In this case the extinction correction should be made from the radio/ $H\beta$ extinction value.

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